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Final Technical Report for NASA Grant NAG 5-1695.
Cooperative Research in Space Geodesy and Crustal Dynamics

This grant covered the period from July 1991 through August 1994. The research covered a number of topics in geodesy and crustal dynamics. Specific topics included:

1. Satellite tracking and gravity field determinations. This supported several NASA satellite projects.
2. Crustal Dynamics. This concentrated on space geodetic site stability for VLBI sites.

Details of the research are appended.

III. CURRENT RESEARCH EFFORTS

Research has been done in several areas including mission design for geopotential mapping from space- and air-borne missions, data analysis for the local and global determination of the gravity field of Earth, Mars, and the Moon, the orientation of the earth in space and its variable rate of rotation from Satellite Laser Ranging (SLR) and Global Positioning System (GPS) observations, reference frame establishment and maintenance for Crustal Dynamics studies, and the improvement of measurement models and estimation procedures within the data analysis software.

1. Future space mission studies for geophysics

Erricos Pavlis has been actively involved in the pre-Phase A and the Phase A studies for a new "Gravity And Magnetism Earth Satellite - GAMES". The recent rejection of the ARISTOTELES mission from ESA's council of ministers would have left the geodetic community without a geopotential mapping mission once again. Geodesists along with solid Earth geophysicists and oceanographers have been trying to launch such a mission since the Williamstown, MA planning meeting in the late sixties. As the first indications of the ARISTOTELES fate came in, Goddard scientists decided to prepare a counter proposal to NASA Headquarters to fill the void created. The objectives of the new mission were to cover as much of the objectives that ARISTOTELES would have achieved. The use of as much existing ("off-the-shelf") technology as possible and maintaining the total cost within the range that was originally allocated within NASA's budget for the ARISTOTELES mission were the most serious constraints for the new concept. After some initial scoping of the problem, it was decided that given the expertise available within GSFC, a laser-transceiver-based design would be the best instrument to produce the high resolution gravitational field required. Dr. Pavlis performed an initial error analysis study to show the sensitivity of the observations and results from such an instrument to various factors, including the altitude of the orbit, the separation between the transceiver and the target, the length of the mission, and the lifetime of the mission as a function of the expected solar activity. The preliminary investigations were presented in June '92 at a NASA Headquarters management group meeting in competition with a similar design by the Jet Propulsion Laboratory group. The Goddard concept was immediately approved for further study. A new date in early November '92 was set to review the new studies.

Dr. Pavlis simulated a complete mission profile for a six-eight month mission depending on the solar activity during the mission. The design involved GPS tracking of the transceiver-carrying main spacecraft and laser satellite-to-satellite tracking of the target from the main s/c. The former providing

the long wavelength information for the gravitational field while the latter senses mainly the medium and short wavelengths. The results of this study were summarized in terms of the error spectrum for the resulting Stokes' coefficients of the field and compared to the signal spectra of the gravitational field, the mean ocean dynamic topography, the atmosphere-induced variations in the gravity field and the post-glacial rebound spectra. Dr. Pavlis presented these results to the NASA management at a meeting in November '92. The result of that meeting was the approval from Headquarters to proceed to a Phase-A study with full support from Goddard management. Exposure of the results and the mission to the International community has been deemed important since these very initial stages. In fact, GAMES is a joint, US-French cooperative mission. In February '93 he participated in the workshop organized by Dr. Colombo and Dr. Chao on TIDES, where he presented a review of the status of gravity modeling efforts of the TOPEX/Poseidon team and the advances expected from the GAMES mission.

During the Phase-A study, Dr. Pavlis has continued to support the team of engineers in finalizing the s/c design and the best mission profile by investigating the impact of variations in key parameters (orbit altitude, launch date, size and shape of main and target s/c), on the results for the gravitational field model. This is expected to continue in the future as the study enters its Phase B.

Considering the impact this mission will have on the interpretation of oceanographic data, it was deemed appropriate to quantify this in a way best understood by the oceanographic community. Dr. Pavlis used the results of the previous study to determine the level to which oceanographic signals could be reliably resolved using the geoid determined from GAMES. By comparison to the current state-of-the-art model, JGM-2, and the aforementioned simulation results, Dr. Pavlis showed that while today we are limited to decimeter accuracy at wavelengths of about 1400km, the geoid from GAMES will deliver similar accuracy at wavelengths of some 280km or less. This five-fold improvement in resolution is of great significance in oceanographic circulation studies. The results were presented at the European Geophysical Society General Assembly in Wiesbaden, Germany, May 3-7, '93. A broader comparison of future geopotential mapping missions was presented in an invited talk at the American Geophysical Union Spring meeting in Baltimore, Maryland, May 24-28, '93. Herein, the results of studies performed over the last three years by Dr. Pavlis, for such missions as Gravity Probe B, TOPEX/Poseidon, ARISTOTELES, and GAMES were summarized and compared. As a member of the Geodesy science sub-group for the Satellite Test of the Equivalence Principle (STEP) mission, Dr. Pavlis investigated the level of accuracy that can be achieved with the current mission profile of the ESA-NASA jointly proposed STEP mission (GPS and gradiometry on a drag-free s/c). The

expected contribution of this mission to our knowledge of terrestrial gravity was first presented at a STEP science workshop at Stanford University, August '92. A short paper on the "Current Status of Gravity Field Modeling" was also presented at the meeting and contributed to the Phase-A report for ESA. The results were later interpreted as improvements to the present knowledge (JGM-1 at the time), and presented at the 7th International Symposium, Geodesy and Physics of the Earth, Potsdam, Germany, Oct. 5-10, '92.

In April of '93, Dr. Pavlis was invited by the STEP Science team chairman, Dr. Ron Hellings of JPL, to give a talk at the STEP Symposium in Pisa, Italy, (April 6-8), on the "Prospects of gravity field modelling from satellites". This included a presentation of the latest Joint Gravity Model 2 results (using TOPEX/Poseidon tracking data), a first exposition to the wider scientific community of the GAMES mission and its impact on geodesy, and the simulation results from Dr. Pavlis' STEP studies during Phase-A. The presentation will appear in the proceedings of the symposium (under preparation). In addition to the contributions and reviewing of the Phase-A report, Dr. Pavlis supplied information and reviewed the final STEP brochure that was recently produced at Stanford.

Dr. Pavlis has been involved in two additional "projects" that will eventually require the analysis of SLR data: the Laser Reflector Experiment (LRE, in cooperation with the Naval Research Lab), a laser array on one of the soon-to-be-launched GPS satellites (tentatively September '93), and MSTI-2, a DoD satellite that will carry a small laser array which we plan to use for atmospheric drag studies. The altitude of MSTI-2 will be only 400km, it is thus a good candidate for studies that will help GSFC analysts understand the prevailing drag environment as it will be encountered by GAMES (altitude 450-250km). The LRE mission will help us understand better the non-conservative forces acting on the GPS s/c and the behavior of the on-board clocks independent of the GPS tracking data and in an unambiguous way. This enhanced modeling can in turn be reversed to improve the positioning results for users of the GPS signals when their solutions are based on the SLR-improved orbital models.

Oscar Colombo worked on a study that has been code-named "T.I.D.E.S." (for Tidal Interferometric DETector in Space). It is a study for a possible mission involving two spacecraft in a common, polar, low Earth orbit (600 km), with advanced laser tracking between satellites to measure their relative accelerations to about 10^{-12} g (g: normal accel. of gravity). The objective would be to map changes in the gravity field associated with large scale mass redistribution in the atmosphere, oceans, and solid earth (primarily related to the watercycle), which could be an entirely new way of observing the effects of global change in climate and in other geophysical

processes. The idea has the support of Code 920 at Goddard SFC.

Several investigators within NASA have expressed their interest in possible uses, ranging from earthquakes to deep ocean currents. A presentation was made in Germany, in October '92, in a joint paper with Dr. Benjamin F. Chao, from Goddard. A one-day workshop was held at Goddard on February 5, 1993, with scientists and engineers from NASA's Goddard SFC and Langley RC, where advanced laser designs for use in space are being developed. Other participants included staff scientists from the Ginzon Physics Laboratory of Stanford University, NASA Headquarters, Joint Institute for Research in Astrophysics, Boulder, Colorado, and other groups with related interests. Possible date for such a mission would be early next decade. The preliminary study has demonstrated that the technology is well on its way to meet the main requirements for such a mission, and that the information to be gained from it could be of great significance and quite unique in some cases. The result of this activity was reported at a meeting of the European Geophysical Society this May, in Wiesbaden, Germany, in an invited paper (with Dr. B. Chao as co-author) on the idea for the T.I.D.E.S mission.

E. J. O. Schrama is visiting from the Delft University of Technology, faculty of geodesy, sponsored by the Royal Netherlands Academy of Arts and Sciences with a one year fellowship. Dr. Schrama is also a member of the STEP geodesy subgroup. In this context two presentations were given at the AGU spring meeting: (a) Absolute calibration of the STEP cross-track gravity gradiometer by means of GPS tracking (a contributed paper) and (b) The Role of STEP as a Gravity Field Mapping Mission (an invited paper).

2. Satellite Tracking Data Analyses and Gravity Field Determination

Oscar Colombo has been involved in research on the 'Precise navigation of aircraft and other vehicles' over long distances (500 - 2000 km) using the Global Positioning System (GPS) of satellites for radio-navigation and positioning. Preliminary studies by Dr. Colombo in 1991 had suggested that instantaneous positions of 0.1-0.2 m accuracy could be estimated, at least once every second, for a moving vehicle regardless of its velocity or distance from GPS(fixed) reference stations. In the last 12 months he has written and tested a program for actual navigation, using data gathered during a complete aero-geophysical survey of Greenland carried out by personnel from the Naval Research Lab. (USA) and the National Mapping and Cadaster Service of Denmark, during 1991-92. Work on this continues, but the outcome so far is quite encouraging. Preliminary results seem to confirm the previous estimates, which could have considerable significance in the remote sensing of remote areas with gravimeters, terrain and ice-profiling altimeters, and other instruments that become more

useful with improved navigation. The accuracy achieved over 630 km compares well with that attained over much shorter distances with ordinary but precise GPS techniques whose effective range is limited to some 100 km from a fixed station. Applications of interest to NASA are in airborne testing of instruments under development for use on satellites, and in scientific aerosurveys that the agency conducts. The results of this investigation were reported at the meeting of the European Geophysical Society this May, in Wiesbaden, Germany. Dr. Colombo will visit the Mapping and Cadaster Group in Copenhagen, Denmark, to continue work on the Greenland GPS data analysis, until late August.

Erricos Pavlis continued to support the GSFC Satellite Laser Ranging data analysis group throughout the year. In particular, the latest SLR solution for Earth orientation parameters from LAGEOS data was evaluated and submitted to the International Earth Rotation Service Central Bureau. The results were also presented at the EGS meeting in Wiesbaden and the IERS workshop in Paris, May 11-13. During the latter, Dr. Pavlis presented the views of GSFC's group on the adoption of new standards for the analysis and modeling of optical (SLR, LLR) and radio tracking (VLBI, GPS) data for earth orientation determination and reference frame establishment and maintenance. In addition to supporting the mainstream analysis of SLR data, Dr. Pavlis continued to analyze, compare and combine the results obtained from the analysis of LAGEOS data and those from radio tracking techniques such as GPS and VLBI.

The results from the International GPS Service (IGS) campaign during the summer of 1992 (EPOCH'92), were intercompared and evaluated vis-a-vis the standard SLR series as well as special solutions that Dr. Pavlis performed specifically for this purpose. The results of these studies were reported at the Potsdam IAG Symposium 112 and at the AGU Fall '92 meeting in San Francisco. In an effort to improve the modeling of geophysical processes within GSFC's s/w (GEODYN II), Dr. Pavlis has worked with GSFC's s/w programmers and analysts to implement additional modeling capabilities. These include the effects of unmodeled nutations (in addition to the IAU1980 model), an updated model for the effects of zonal tides on the earth's rotation rate, the inclusion of the diurnal and semi-diurnal effects of ocean tides on polar motion and earth rotation as well as their effects on the origin of the crust-fixed coordinate frame of the tracking network. His analysis of the entire LAGEOS data set for 1992 with some of these models in place, indicated the important role they play in interpreting the observed variations at today's sub-centimeter accuracy levels. These results were presented at the Spring '93 meeting of the AGU.

During 1992 and early 1993, Dr. Pavlis participated in the completion of the TOPEX/Poseidon pre-launch and the tuned post-launch version of the Joint Gravity Models 1 and 2 respectively.

In the past year he has been leading the effort to improve the modeling of GPS data collected onboard satellites within the GEODYN II s/w package. Dr. Pavlis developed several s/w preprocessing packages required for the reduction of the TOPEX GPS Demonstration Receiver data within this environment. He has been in close cooperation with the project scientists, engineers and analysts at JPL, to ensure the proper modeling of the data. Work has commenced on the analysis of an initial data set of four days tracking in October '92, in order to evaluate the performance of the s/w. During the Spring '93 meeting of the AGU, JPL scientists announced the release of an additional six 10-day cycles of GPSDR data. It is anticipated that a significant portion of his time during the upcoming year will be devoted in the analysis and reduction of that data for Precision Orbit Determination and gravity field improvement.

Dr. Pavlis has been the advisor of a PhD student, T. Robert Olson, from the University of Colorado's Center for Astrodynamics Research who is holding a fellowship from NASA's Laboratory for Terrestrial Physics. In that capacity he is providing guidance in the student's research and supervises his progress. He is also facilitating the release of tracking data required for the student's work. The topic of Mr. Olson's dissertation is the "Evaluation of Spaceborne Tracking Techniques for Geophysical Applications". This requires the analysis of laser, GPS, Doppler and TDRSS satellite-to-satellite tracking data. Results from the analysis of data from the Explorer Platform GPS receiver were presented at the Fall '92 AGU meeting and at the EGS '93 meeting in Wiesbaden. It is expected that Mr. Olson will complete his work within the upcoming year.

In a continuing effort to improve GSFC's data analysis capabilities, Dr. Pavlis has arranged for an additional fellowship for a PhD student, Mr. David Chadwell, at The Ohio State University's Dept. of Geodetic Science and Surveying, under the supervision of Prof. Clyde Goad. Mr. Chadwell is extending GEODYN's estimation capabilities to allow for stochastic modeling of parameters in a Kalman filter scheme. Dr. Pavlis is acting as the technical monitor and provides guidance and a liaison between the student's advisor and the GEODYN programmers and analysts group. This effort is expected to continue through the upcoming year.

Frank Lemoine is focusing on research in the area of planetary and interplanetary geophysics. Dr. Lemoine's principal research effort is the determination of the gravity field of Mars based on analysis of the Mars Observer tracking data, in collaboration with other GSFC investigators. He is also investigating the correlation between topography and gravity on Mars and its implication for geophysics. Dr. Lemoine is a member of the Precise Orbit Determination team (POD) at NASA/GSFC, with primary goal the determination of precise orbits for the Mars

Observer Laser Altimeter (MOLA).

Dr. Lemoine is also involved in the estimation of the GM of the Martian moons Phobos and Deimos, using the indirect flybys (distant encounters), rather than the close approaches. This technique takes advantage of the more numerous distant encounters as opposed to the small number of close flybys (less than 300 km). Determination of improved orbits for these bodies will be achieved through reanalysis of the Phobos and Deimos astrometric data from Mariner 9 and the Viking Orbiters. In particular, in light of the development of the new gravity model for Mars to degree and order 50, it is possible to produce improved spacecraft ephemerides that will reduce the uncertainty in the s/c positions. This has been a major source of uncertainty in the astrometric observations. Determination of the Phobos and Deimos orbits is related to issues of determining the secular acceleration of these bodies towards Mars (for Phobos) and away from Mars (for Deimos). It may indirectly make a contribution to constrain the planet's precessional constant.

Dr. Lemoine is also involved in the investigation of the albedo and thermal IR perturbations on planetary orbiters. POD work for LAGEOS has shown the importance of including models of the Earth's albedo and thermal emission. With the increasingly stringent OD requirements for planetary orbiter missions, these albedo and thermal IR perturbations must also be included in the force models for s/c in orbit about Mars, the Moon and Venus. Using the best possible sources of data (Viking/Infrared Thermal Mapper Instrument and the MO/TES instruments) it is possible to obtain models and ascertain their effects on the orbits of spacecraft. Using similar data for Venus or the Moon (from the NIMS instrument on Galileo) it may be possible to derive similar models for these bodies and investigate their effects on future missions like Clementine and missions like PVO and Magellan.

Dr. Lemoine is also a co-investigator in the Lunar Geodesy and Topography investigation for the Clementine mission to the Moon.

E.J.O. Schrama has been involved with a number of research topics, some new, others a continuation of research from his previous visit at GSFC.

Dr. Schrama is actively participating in the TOPEX/Poseidon radar-altimetry data analysis. Currently software is being developed to aid the analysis of the T/P altimeter data. Results will be presented at the AGU fall meeting in December '93.

Error analysis software has been developed to evaluate the statistics of recent combined solutions for gravity field and dynamic sea surface topography models developed within GSFC's Space Geodesy branch. This is a follow-up of his activities in

1990. The error analysis software is frequently used to verify the error behavior of the most recent gravity models developed within Code 926.

3. Reference Frame Establishment and Maintenance for Crustal Dynamics

The establishment and maintenance of a precise global reference frame for the study of Earth kinematics and dynamics has been a fundamental task of space geodetic systems since their inception. GSFC has been in the forefront with their analyses of the data from their optical, laser and VLBI tracking networks. The effort that created the first centimeter-precision global network, the 'Crustal Dynamics Project', was succeeded last year by a new program, the Dynamics Of the Solid Earth (DOSE) program. Related to DOSE, a new global tracking network is being established under the acronym FLINN, (for Fiducial Laboratories for an International Natural science Network). This network will encompass the previously deployed tracking systems and will be expanded by several (order of 180) GPS stations with a global distribution, ultimately reaching more than 200 unique sites around the world. This requires in addition to the usual analysis of the collected data, the selection of the future sites within the regions with no present coverage and the survey of those regions by geologists to identify the most appropriate location in terms of stability of the terrain. The last issue is vital in properly interpreting the observed motions and not confusing them with local effects. As one of the principal investigators in a DOSE-funded proposal, Dr. Pavlis is in close contact with the Canadian colleagues (co-investigators) in coordinating observing schedules and collaboration in the analysis of the collected data. The goal of this investigation is the characterization of the Post-glacial rebound signal over the Laurentide region. Dr. Pavlis had an extensive discussions with Dr. A. Lambert of the Canadian Geological Survey (CGS) during the DOSE meeting at GSFC in October '92 and at the EGS meeting in Wiesbaden. Among other issues discussed was the future deployment schedule of SLR, GPS, and absolute gravity measuring apparatus in the eastern and south-eastern region of Canada. NASA's transportable laser is currently collecting data at Algonquin Park Radio Observatory near Ottawa, Canada. CGS will perform some of the absolute gravity surveys this year and it is expected that next year they will be joined by the U.S. National Geodetic Survey (NGS) team to complete the observation of two major traverses. Positioning of the sites will be done by means of GPS and the data will be analyzed at GSFC, CGS, and NGS. Dr. Pavlis is in discussions with Dr. W. Carter of NGS to assert that the chosen sites will be sufficiently close to those originally proposed. A collaboration between the U.S. and Canadian agencies is important for the success of the project and the reduction of the overall expenses by sharing resources.

The results of GSFC's latest global solution (SL8.2) for the site coordinates of the SLR network were delivered to the IERS/CB for the development of the IERS Terrestrial Reference Frame '92 (ITRF92) at the Paris workshop. This is the first time that the site velocities are simultaneously estimated within the data reduction process, using a new s/w capability that Dr. Pavlis had suggested in 1989. In an effort to extend, compare and unify the SLR and GPS tracking networks, Dr. Pavlis has processed the entire IGS campaign GPS data set and is now reducing the data using GSFC's GEODYN II. The three month data set from some twenty six globally distributed sites (most collocated with SLR and/or VLBI sites) will result in the realization of a GPS-based reference frame with strong ties to the older, more mature techniques of SLR and VLBI.

The large scale kinematics of the SLR network as characterized by the linear velocity estimates from the global solution SL8.2 are being summarized in an article for the Geophysical Journal International with Dr. Pavlis as a co-author.

The DOSE and FLINN networks are supported by Dr. Allenby in selecting future sites and in establishing records of local effects for the already existing sites. He performs geological reconnaissance of the regions where future systems are to be deployed and coordinates the project requirements and priorities with the parties executing the local surveys. As part of the effort of characterizing local effects around the main observatories in the network, he leads the planning of "footprint" surveys and their periodic re-observation. Dr. Allenby collects the pertinent information and maintains a catalog for future reference. His long-standing involvement in this effort benefits the project through the coordinated use of existing sites of NASA as well as other cooperating agencies and keeping the costly establishment of new sites to a minimum. Dr. Allenby is extending his efforts to include information on international sites through his contacts with colleagues at these agencies.

In addition to his field work, Dr. Allenby is also the assistant chairman for the International Space Geodetic Measurement Sites (SGMS) subcommission of the International Association of Geodesy. In that capacity he prepares the correspondence with the members, organizes the committee meetings, drafts the annual reports, and prepares, edits and distributes the SGMS newsletter. He also acts as the liaison between SGMS and other subcommissions.

IV. FUTURE EFFORTS

Most of the projects discussed in section III are ongoing ones and reference is made in that section to the work which will

be done in the coming year.

Oscar Colombo will be involved in the analysis of data obtained by in an aero-geophysical survey of Greenland by the US Naval Research Lab. and the Danish Mapping authority. He will also continue his study on the use of ultra-stable laser interferometry in space to detect variations in the Earth's gravity field. He also continues as co-investigator of the tidal analysis science team in support of the NASA/CNES TOPEX/Poseidon mission.

Erricos Pavlis will continue his involvement with the analysis of the LAGEOS SLR data for Earth orientation, reference frame and crustal deformation studies. This is an ongoing project which aims at providing the large scale framework within which the Global Positioning System observations can be used to determine local deformation fields. As a co-investigator in the LAGEOS-II data analysis proposal, he will also work on the combination of that data with the LAGEOS data in an effort to improve both, the kinematic results from the next SLR global solution as well as the low degrees and orders of the gravity field model. The analysis of SLR and GPS data from recent campaigns will focus on two issues: (a) the determination of high-frequency Earth Orientation Parameters using the improved models implemented in GEODYN, and (b) the optimal combination of SLR tracking data from several satellites (LAGEOS, LAGEOS II, Starlette, ETALON I & II, Ajisai, and the soon to be launched French satellite STELLA) for a precise 3-dimensional positioning of transportable systems. Both efforts will benefit the post-glacial rebound investigation studies. Previous work on enhancements to the GEODYN software package can now be exploited to analyze GPS and SLR data. The preliminary four-day results from TOPEX/Poseidon's GPSDR data will be extended with the newly acquired data for six complete 10-day cycles. The results will be included in the next improvement of the gravity field model produced within GSFC. Effective July 1, 1993, Dr. Pavlis has been elected a Corresponding Member of the IERS Directing Board. In that capacity he has agreed to provide IERS annually with a series of EO parameters derived from the latest GSFC SLR solution. Additionally, support of the IERS GPS Service in evaluation of the results will continue. The solution for site coordinates from the 1992 Campaign will be submitted to the IERS for inclusion in the compendium of results (under preparation). The support of the GAMES Project during Phase-B will continue and it is anticipated that more complex and realistic simulation studies will be required in the upcoming phase as the design of the s/c and the instruments becomes better defined. Dr. Pavlis is presently in discussions with several companies that design and manufacture GPS receivers in an effort to determine the viable options available to GAMES. This will continue until enough information is collected to support a decision-taking process. It is anticipated that the advisory duties for the two PhD

students will continue until their graduation later this year. It is also anticipated that work will continue on the study of the benefits and contribution of the GPS tracking data to the determination of the gravity field from gradiometry measurements on the new mission that will replace the STEP proposal to ESA (tentatively named): Eötvös.

Frank Lemoine will be working on the POD for Mars Observer and the reduction and analysis of the MOLA data for the determination of the Martian topography. Dr. Lemoine will also be involved with the data analysis for the Lunar Geodesy and Topography investigation from the Clementine mission to the Moon.

E.J.O. Schrama will continue providing support to the TOPEX/Poseidon altimeter data analysis group for sea-surface topography determination and the evaluation and visualization of the statistical properties of future solutions.

Richard Allenby will continue with his duties as assistant chairman of the SGMS and will provide the required support for the reconnaissance of new sites as required by the program management.

V. PUBLICATIONS AND PRESENTATIONS LIST

OLC Publications

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1992 Colombo, O.L., Chao, B.F., "Global Gravity Change in 2001", Proc. I.A.G. Symposium 112, "Geodesy and Physics of the Earth", Postdam, Germany, Oct. 1992 (in press).

1992 Colombo, O.L., "Precise Differential GPS Navigation for Long-Range Airborne Geophysics", Proceedings International Workshop Honoring George Veis "Global Positioning Systems in Geosciences", Tech. Univ. of Crete, Chania, Greece (in press).

1992 Colombo, O.L., "Precise GPS Orbits for Geodesy", Proceedings COSPAR Meeting PM-1, XXIX COSPAR Plenary Meeting, World Space Congress, 1992 (in press).

1992 Colombo, O.L., and Peters, M.F., "Precision long-range DGPS for airborne surveys", GPS World, Vol. 3, No. 4, Aster Publishing Co.

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Proceedings of 6th International Symposium on Satellite Positioning, Columbus, Ohio, March 17-20.

ECP Publications

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1992 Pavlis, E.C. and L.E. Braatz, "A Global Reference Frame for Geodynamics From GPS, SLR and VLBI", in Proceedings of International Workshop on "Global Positioning Systems in Geosciences", Honoring Prof. George Veis, Tech. Univ. of Crete, Chania, Greece (in press).

1992 Pavlis, E.C., "Current Status of Gravity Field Modeling", STEP Science Team Workshop, Stanford University, August 24-27.

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1992 Pavlis, E.C., (with T.R. Olson), "Preliminary Evaluation of the GPS-based Orbit Determination of the Explorer Platform (EP)", Eos Trans. AGU, 73(43), Fall Meeting Suppl., 131, 1992.

1992 Pavlis, E.C., "Earth Orientation Results From LAGEOS Satellite Laser Ranging and GPS Data From EPOCH'92", Eos Trans. AGU, 73(43), Fall Meeting Suppl., 135, 1992.

1992 Pavlis, E.C., "Global Geodesy at the Cross-roads", Invited presentation in honor of Prof. Ivan I. Mueller, Eos Trans. AGU, 73(43), Fall Meeting Suppl., 118, 1992.

1993 Pavlis, E.C., "Prospects of Gravity Field Modelling from Satellites", in Proc. of STEP Symposium, Pisa, Italy, April 6-8, 1993 (in press).

1993 Pavlis, E.C., (co-author), "STEP (Satellite Test of the Equivalence Principle)", Report on the Phase A Study, ESTEC Report SCI (93) 4.

1993 Pavlis, E.C., (co-author), "Expected Orbit Determination Performance for the TOPEX/Poseidon Mission", IEEE Transactions on Geoscience and Remote Sensing, Vol. 31, 2, March 1993.

1993 Pavlis, E.C., "Improved Gravity Field Models From Future Space Missions", European Geophysical Society XVIII General Assembly, Wiesbaden, Germany, May 3-7, 1993.

1993 Pavlis, E.C., and T.R. Olson, "Precise Orbit Determination From GPS Tracking", European Geophysical Society XVIII General Assembly, Wiesbaden, Germany, May 3-7, 1993.

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1993 Pavlis, E.C. and several others, "Contemporary global horizontal crustal motions", manuscript being submitted to Geophysical Journal International.

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1993 Smith, D. E., F. J. Lerch, R. S. Nerem, M. T. Zuber, G. B. Patel, S. K. Fricke, and F. G. Lemoine, An improved gravity model for Mars: Goddard Mars Model 1 (GMM-1), accepted to J. Geophys. Res., 1993.

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EJOS Publications

E. Schrama, Some Remarks on Several Definitions of Geographically Correlated Orbit Errors: Consequences for Satellite Altimetry, Manuscripta Geodaetica, Vol. 4, 1992.

E. Schrama, (co-author) STEP geodesy co-experiment, Stanford University workshop, August 25, 1992.

RA Publications

Contributions to the SGMS Newsletter:

The CDP Site Stability Project: Geodetic Footprinting of CDP VLBI/SLR Observing Sites Using GPS", (co-author), Vol.2,1.

GSFC's Space Geodetic Footprinting Program: Progress Report, (co-author), Vol. 3,1.

Global Fiducial Observing Stations, (co-author), Vol.3, 2.

GSFC's geodetic Survey Support at Major Sites Employing Space Measurement techniques: Progress Report, (co-author), Vol. 4, 1.

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 Cooperative Research in Space Geodesy & Crustal Dynamics
 November 15, 1993 through June 30, 1994
 Off Campus

I.	Personnel		
	E. Pavlis, Principal Investigator, 7.5 months ef	37,000	
	O. Colombo, 7.5 months	42,188	
	F. Lemoine, 7.5 months effort	26,563	
	Research Graduate Assistant, 7.5 months effort	8,625	
	J. Perini, 7.5 months effort	13,125	
	Hourly Personnel	21,875	
	Total Salaries	149,376	
II.	Fringe Benefits	38,250	
III.	Publications	2,000	
IV.	Travel	39,000	
	Total Off-Campus Direct Cost	228,626	
V.	Indirect Costs (26% of MTDC)	59,443	
	Total Off-Campus Cost	288,069	

On-Campus

I.	Personnel		
	J. D. Trasco, Co-P. I., Part-time effort	3,000	
	Computer Support Staff	9,375	
	Research Graduate Assistant, 7.5 months effort	8,625	
	Hourly/Clerical/Secretarial	4,000	
		25,000	
II.	Fringe Benefits	7,575	
III.	Travel-Domestic Scientific Meetings	3,000	
IV.	Communications, Supplies, and Materials	1,500	
	Total Direct Cost	37,075	
V.	Indirect Cost (48% of MTDC)	17,796	
	Total Cost-On Campus	54,871	
	Total On and Off Campus	342,940	

III. Current Research Efforts

Research has been done in several areas including determination of the gravity field of the earth and crustal dynamics. Details are given in the following as well as a list of publications which resulted from this work.

1. Satellite Tracking and Gravity Field Determinations

Oscar Colombo has been investigating the combination of inertial sensors with GPS navigation to do very precise airborne altimetric and gravimetric surveys for geophysical, oceanographic and ice studies. One application of this work will be to help analyze data from the current aerial survey of Greenland by teams from the U.S.A. and Denmark. He has begun exploring the possible use of ultra-stable laser interferometry in space to detect variations in the earth's gravity field associated with a variety of geophysical phenomena. He is now a member, since March '92, of the Science Team of the SUNLITE project (run from NASA's Langley Research center).

Last year Colombo became a Fellow of the International Association of Geodesy, and was the President of the Special Study Group of the IAG for Precise Orbit Determination until the General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Vienna, in August. He continues as a co-investigator in the U.S.A. tidal analysis science team for the joint NASA/CNES TOPEX/POSEIDON oceanographic space mission.

Colombo organized and chaired a special session on geophysical applications of precise GPS navigation for the 1991 Spring Meeting of the American Geophysical Union, and has been main convenor and editor of the proceedings of the international IAG Symposium on Gravity Field Determination by Space and Airborne Methods that took place during the General Assembly of the IUGG, in Vienna.

Colombo attended several meetings, presenting at all of them his latest results: AGU Spring Meeting in Baltimore (in June), and Fall Meeting in San Francisco (December); General Assembly of the IUGG in Vienna (August), GPS-91 (Institute of Navigation, or ION) in Albuquerque (in September), and the Sixth International Symposium on Satellite Positioning in Columbus, Ohio (March '92). He contributed to the Proceedings of the IUGG, ION and Columbus meetings.

The analysis and interpretation of the LAGEOS SLR data set 1976-1988 was summarized by E. Pavlis in NASA Technical Memorandum 104549 published in September of last year. The focus of this year's activity has been the determination of crustal motions and deformation fields from the combined analysis of GPS and SLR data. Eventually, these will be combined with VLBI results to form a complete and uniform result that describes the global changes on the surface of the planet in all four dimensions. A robust instantaneous estimate of the state of the system defined by the site coordinates of the SLR stations has been obtained through the recent re-analysis of the LAGEOS SLR data from 1980 through 1991. Subsequently, we only need to periodically determine the changes of the state with respect to time, monitoring the deformation at all the participating sites. The SLR positions will be compared and combined with the recent GSFC VLBI solution to provide the large scale framework within which the GPS observations are used to "interpolate" the deformation field.

The GSFC software (GEODYN) now has the capability of batch processing the GPS data, pseudo-range and carrier phase. A large number of additional S/W packages have been developed to handle the re-formatting, preprocessing, editing, and staging of the raw GPS data for further analysis with GEODYN. In addition to our local package we have also acquired MIT's GAMIT and, JPL's GIPSY packages. These have been installed and are available for analyses and intercomparisons. We have also developed the required S/W for the evaluation and post-processing of the results. The entire system has been used to analyze and report on the data collected during the GPS IERS and Geodynamics Campaign 1991, (GIG'91), presented at the Fall AGU meeting and The Ohio State University meeting on Satellite Positioning. We have also analyzed the first four days of data from the Alaska '90 GPS campaign, and preliminary results were reported at the XX General Assembly of the IUGG, in Vienna, Austria. At present we are in the process of developing a solution that is based on the GIG and con-current SLR data; this will serve as a starting point for the final 3-way combination solution.

GSFC is an associate analysis center for the 1992 IERS GPS Service Campaign and in this capacity we will provide IERS and the international community with results from the analysis of the GPS data acquired during the campaign. This three-month data set is likely to be the

most robust and most appropriate one to use in determining the initial combined solution from all three space techniques (i.e. SLR, VLBI, and GPS).

Considerable effort was also applied in supporting the re-iteration solution for the TOPEX/Poseidon pre-launch gravity field. The new analysis is now fully compatible with the models and parametrization used in the analysis of the LAGEOS data. This allows for direct exchange of input data, setups, results between the two groups and economizes in use of computer time and manpower. We are nearly at the end of the process and as soon as the results become available there will be a reference frame intercomparison between this solution (based on data from over 33 satellites and hundreds of stations) and the one derived exclusively from the LAGEOS data analysis.

Other areas of work include the feasibility studies for future missions for gravity mapping such as GP-B, ARISTOTELES, and STEP, as well as the development of new concepts and missions for the same purpose. Results were presented during the IAG Symposium No. 3 and will appear in the soon to be published proceedings. More recently, these studies were discussed within the framework of the STEP working group (geodesy sub-group), in order to prepare for a new simulation study commissioned by that group, to determine the benefits and contribution of the GPS tracking data on the gradiometry-based gravity field from STEP. This study will be completed and presented at the next meeting of the group in late August of this year.

2. Crustal Dynamics

Lynda Bell has continued work on the space geodetic site stability project for NASA/GSFC's Crustal Dynamics Project (CDP). The objective of this project is to assure the integrity of geodetic measurements taken at CDP VLBI/SLR observing monuments by implementing and measuring local GPS networks around the main observing monument. In a tectonically active areas, these GPS sites should demonstrate that the main CDP site moves as expected within the strain environment in which it is located. In a tectonically stable area, these sites should be located within the same lithotectonic block as the main observing monument. Responsibilities include locating potential GPS sites around critical CDP observing monuments. This entails performing a geologic reconnaissance of the applicable area along with extensive background research and cooperation with local university or government agencies. Direction is given to project surveyors on where to set up GPS instruments at each of these sites. Analyses of the GPS data is coordinated and interpretation of the final results is completed. The project has completed nine site stability surveys with GPS and eight reference mark resurveys between June 1990 and December 1991. Geologic reconnaissance has been done at many of these sites including two VLBI sites in Alaska, several VLBI sites with the California plate boundary zone, and the Westford fiducial VLBI site in Massachusetts. This project also supports NASA's FLINN network, a fiducial network of geophysical observatories located across the world. Work on this project has included analysis of the GPS data, a multi-agency software intercomparison using GPS processing software, participation in a GPS working group at Goddard, and engineering

analysis of high precision space geodetic monuments. All of these projects have been completed under the support of John Bosworth, CDP Project Manager, NASA/GSFC.

In addition to the above mentioned project, work has continued on modeling and understanding crustal deformation fields near the Alaska-Aleutian subduction zone using VLBI, GPS, leveling, and trilateration data. Intensified dislocation and finite elements modeling of coseismic displacement associated with the 1987-1988 Gulf of Alaska earthquakes measured near Yakataga, Alaska with VLBI has resulted in several AGU abstracts (reported on previously) in addition to several journal articles listed below. All of the research on the Alaska-Aleutian subduction zone has been completed in collaboration with Dr. Jeanne Sauber, Geodynamics Branch, NASA/GSFC.

Publications

Bell, L., G. Mader, M. Schenewark, C. Vigny, R. King, B., Schutz, CD., Wilson, M. Bryant, E. Pavlis, and V. Nelson, Precision of the 1990 Fort Davis Site Stability Survey (abstract), *EOS Trans.* AGU, 72, 1991.

Bell, L., and M. Bryant, An Overview of Existing Permanent GPS Monuments in the U.S. and Canada, in *Space Geodetic Measurement Sites Subcommittee Newsletter*, part of the International Coordination of Space Techniques for Geodesy and Geodynamics (GSTG), Vol. 3, No. 1, March 1992.

Bell, L., M. Bryant, and R. Allenby, Goddard Space Flight Center's Space Geodetic Footprint Program: A Progress Report, in *Space Geodetic Measurement Sites Subcommittee Newsletter*, part of the International Coordination of Space Techniques for Geodesy and Geodynamics (GSTG), Vol. 3, No. 1, March 1992.

Bryant, M., L. Bell, V. Nelson, and R. Allenby, The CDP Site Stability Program in California (abstract), *EOS Trans.*, AGU 72, 1991.

Colombo, O.L., and Peters, M.F., Precision long-range DGPS for airborne surveys, *GPS World*, Vol. 3, No. 4, Aster Publishing Co. 1992.

Colombo, O.L., Airborne gravimetry, altimetry, and GPS navigation errors, *Proceedings IAG Symposium on Determination of the Gravity Field Space and Airborne Measurements*, Vienna, 1991; Springer-Verlag, N.Y., in press.

Colombo, O.L. (editor), From Mars to Greenland: Mapping Gravity with Space Airborne Instruments, *Proc. I.A.G. International Symposium on Gravity Field Determination from Space and Airborne Measurements*, Vienna, August 1991, Springer-Verlag, N.Y., in press.

Colombo, O.L., Errors in long-distance kinematic GPS, *Proc. Inst. of Navigation (ION) GPS-91*, ION Satellite Division 4th International Technical Meeting, Albuquerque, New Mexico, September 1991.

Colombo, O.L., and Watkins, M.W., Satellite positioning, *Rev. of Geophys.*, "Contributions in Geodesy", Supplement, *U.S. National Report to the International Union of Geodesy and Geophysics 1987-1990*, Washington.

Ma, C., J.M. Sauber, L.J. Bell, T.A., Clark, D. Gordan, W.E. Himwich, and J.W. Ryan, Measurement of Horizontal Motions in Alaska Using Very Long Baseline Interferometry, *J. Geophys. Res.*, 95, 21991-22011, 1990

Sauber, J.M., T.A. Clark, L.J. Bell, M. Lisowski, C. Ma, and D. Caprette, Geodetic Measurement of Static Displacement Associated with the 1987-1988 Gulf of Alaska Earthquakes, in *Space Geodesy and Geodynamic*, D. Smith, Kadinsky-Cade, and T.L. Fishetti (editors), AGU Special Publication, AGU Monograph on the CDP (in press), 1992.

IV. Future Efforts

It is anticipated that research will continue in many of the same areas as were covered in the past 12 months. Details of the proposed efforts in the various areas follows.

1. Satellite Tracking and Gravity Field Determinations

Most of the projects discussed in section III are ongoing ones and reference is made in that section to the work which will be done in the coming year. Oscar Colombo will be involved in the analysis of data obtained by in an aerial survey of Greenland by the US and Denmark. He will also continue his work designed to study the use of ultra-stable laser interferometry in space to detect variations in the Earth's gravity field. He also continues as Co-Investigator of the tidal analysis science team in support of the NASA/CNES TOPEX/POSEIDON mission. Erricos Pavlis will continue his involvement with the analysis of the LAGEOS SLR data. This is an ongoing project which aims at providing the large scale framework within which the Global Positioning Satellite observations can be used to determine the deformation field. Previous work on enhancements to the GEODYN software package can now be exploited to analyze geodynamical data. Initial efforts in studying data from Alaska will be continued and expanded. This will also aid in the GSFC support of the 1992 IERS GPS Service Campaign. It is anticipated that the work involving the re-iteration solution for the TOPEX/POSEIDON pre-launch gravity field will be completed. This will result in a reference frame intercomparison between this data and that derived from the LAGEOS data analysis. It is also anticipated that work will be completed on a study to determine the benefits and contribution of the GPS tracking data to the determination of the gravity field from gradiometry measurements of STEP.

2. Crustal Dynamics

Lynda Bell will continue her efforts for the Crustal Dynamics Project (CDP). This involves identification and analysis of information about local CDP sites in order to assess possible motion of these sites which provide the framework for overall tectonic motions. The work specifically will involve determining sites for local GPS networks around CDP sites. Once the sites are determined, a geologic reconnaissance is done along with research into the long term geologic background of the area. This is used to provide direction to the site surveyors for placement of the GPS instruments.

Bell will also continue work already begun on interpretation of the Alaska-Aleutian subduction zone. This will extend modelling of this area which was already begun.

Richard Allenby will continue consulting work for the Crustal Dynamics Project. This will involve occasional site visits and providing liaison with other groups involved in crustal dynamics projects.